



Review

Fiber-reinforced polymer matrix composites for improved defence armor - A comprehensive review

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ABSTRACT

Fiber-reinforced polymer (FRP) matrix composites are prominent defensive armor materials owing to their excellent strength-to-weight ratio and design flexibility. High-strength fibers such as aramid, carbon, or glass embedded in a polymer matrix exhibit excellent impact resistance and energy absorption, which significantly improves ballistic protection. Research by the Defense Research and Development Organisation (DRDO) on FRP's and stealth technologies has helped the Indian military create and use high-performance materials. FRP's are often utilized in the motor and construction sectors, but they may be expanded to a high degree of skeletal uses, such as bullet-resistant and robust devices. The ballistic impact mechanism is directly correlated to the material, fabrication process, strengthening mechanism, thickness, applied projectile parameters, and density. The proposed in-depth review examines the production processes and use of novel ballistic protection materials in bulletproof vests and body armor in the military. It also offers some suggestions for materials that would be good choices for future, all-encompassing body armor.

1. Introduction

Fiber-reinforced composites (FRCs) are essential in engineering because of their excellent mechanical qualities, design flexibility, and light weight. These materials have carbon, glass, or aramid fibers inserted into a polymer, metal, or ceramic matrix. This design combines the high tensile strength and stiffness of the fibers with the toughness and ductility of the matrix to achieve excellent structural performance. The aerospace and automotive industries use carbon fiber-reinforced polymers (CFRPs) as structural components to reduce weight and improve fuel economy and performance without sacrificing strength [1]. Anisotropic fiber-reinforced plastics (FRPs) allow engineers to modify mechanical qualities by positioning fibers to resist certain load routes, thereby improving the load-bearing efficiency. FRCs are widely utilized in civil engineering to reinforce concrete, build bridges, and upgrade old infrastructures. Concrete beams and columns reinforced with glass fiber-reinforced polymers (GFRPs) withstand corrosion and fatigue, particularly in marine and chemical environments. Lightweight and rigid FRCs are used to make turbine blades for wind energy, ensuring aerodynamic performance and durability.

FRCs are suitable for high-temperature power plants and precision

equipment applications because of their thermal stability and vibration damping. As material science advances, FRC's are being used in engineering to solve sustainability issues and to create high-performance, energy-efficient systems. Defence systems using FRCs improve survivability and operational efficiency by reducing the logistical loads. FRCs are lighter than steel armor, which improves the mobility and efficiency of military vehicles [2]. Recent advances in fiber and matrix materials and production methods have made FRC a major component in lightweight, robust armor systems for current military applications [3]. Lightweight aramid and CFRP composites provide improved ballistic resistance and mobility for personal and vehicle armor [4]. India has developed radar-absorbing materials (RAM) using carbon nanotubes and conductive polymers to improve aircraft and naval stealths. India can now produce superior, locally sourced military materials for contemporary combat stealth and protection [5]. FRCs are increasingly being used in military and security applications, highlighting their importance in current defense strategies. The strength-to-weight ratio, corrosion resistance, and impact absorption of sophisticated composite materials make them popular in military aircrafts, naval vessels, and ground vehicles worldwide.

The US, China, Russia, and the EU have invested substantially in FRP

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composite technology for next-generation armour solutions, such as UAVs, lightweight ballistic shields, and reinforced military buildings. The stealth uses of FRP composites, especially those with radar-absorbing materials (RAM), have revolutionized contemporary warfare by improving aircraft and marine vessel survivability against sophisticated radar detection systems. Hybrid and multifunctional composites with nanoparticles for self-sensing and adaptive camouflage are advancing military technology and keeping FRP composites essential for defense applications globally. These advances demonstrate the importance of FRP materials in defining military operations and ensuring worldwide security and strategic defence.

1.1. Importance of defence armours

The military sector requires ballistic protection to defend soldiers, vehicles, weapons troops, and structures against bullets, shrapnel, and explosive pieces [6]. Ballistic protection relies on sophisticated materials science to reduce the kinetic energy and prevent penetration with high hardness, energy absorption, and failure-resistant qualities. Tensile strength, toughness, and hardness are used to evaluate ballistic protection, and ceramics (B_4C , SiC), metals (Ti, Al, Mg alloys), and fiber composites (aramid and polyethylene) show promise. Multi-layered composite structures absorb and spread impact energy while remaining lightweight to combat agility [7,8]. Nanomaterial integration improves the ballistic resistance by improving the structural matrix, making the armor lighter and stronger. In current asymmetric warfare, ballistic protection advances improve operational survival and tactical dominance by allowing defending troops to resist high-energy attacks without compromising mobility [9,10].

Indian defense data shows considerable hurdles and the need for strong ballistic protection materials. The Indian military lost 23 personnel to weapon systems and training incidents by 2023. In addition, operational preparedness problems have occurred, including naval mishaps, which cause major financial losses and deaths. The frequency of mishaps has prompted questions regarding military safety regulations and equipment dependability [11–13]. The Ministry of Defense also noted an upsurge in terrorist assaults in several locations, emphasizing the need for improved ballistic protection for troops and equipment. Armed conflicts increased in 2023, with border skirmishes and non-state actors requiring sophisticated protection measures such as FRP's. Attacks, accidents, and requirements for ballistic-resistant composites threaten the Indian military. Statistically, India faces border conflicts and standoffs with Pakistan and China. In 2022, five MiG-21 fighter planes, a vintage fighter variant, crashed, emphasizing the need for better and more robust materials and technologies [14].

Missile testing and military AI spending demonstrate India's focus on defense upgrades. Successful BrahMos and Agni-3 missile tests and other defence endeavors to improve military preparedness are notable missile developments. Maintenance concerns, especially with older equipment, highlight the need for newer, accident-resistant materials, especially as the government confronts strategic pressure to modernize within financial limits [15]. First, the basic ballistic mechanism must be understood in order to build advanced materials. Generally, foreign objects can create ballistic impact loads on aircraft, boats, power exchanges, and vehicle frameworks, including bird hits, hailstones, bullets, airplane runways, fragments, and explosive fragments [16,17].

In addition to piercing, such impacts may cause widespread delamination, leading to structural performance impairments in FRP's. Most buildings are not designed with armored forces; thus, understanding their reaction to ballistics and damage processes is crucial because of the likelihood of high-speed, low-quality pieces [18]. Previously made from woven materials sewn together, ballistic soft body armours today use laminates layered with nonwoven unidirectional (UD) layers and mixtures of both for better structural stability.

1.2. Objectives and scope of the proposed review

Contemporary protective clothing is either hard or soft depending on the material. In general, a hard body armor provides higher protection than a soft armour, whereas a soft body armor with suitable ballistic protection is appreciated for versatility, portability, and convenience. A hard body armour is composed of ceramics, reinforced polymers, metal plates, and composites. Soft-body armor has numerous layers of ballistic fiber-based high-performance materials [19,20]. Fig. 1 shows the shape of bullet with ballistic mechanism and graphical illustration of projectile impact on the laminate. This review discusses the threats posed by ballistics to both individuals and military property, and aims to provide readers with information that will help them stay abreast of the latest breakthroughs in ballistic-resistant materials research as well as novel materials, techniques, and insights

To gain an understanding of the fundamentals of prior studies, the Science Direct and Google Scholar databases for publications published within the last five years that dealt with topics including ballistics, impact, FRCs, and defense. A total of 13,967 articles (overall) were retrieved from the search; among these, 10,677 were found in Science Direct and 12,900 in Google Scholar. The increasing trend in research on ballistic-resistant defence materials is clearly seen in Fig. 2. The creation of new ballistic protection systems that may raise the military sector to the next level remains a significant unmet need, despite the enthusiasm of scientists and researchers worldwide for the use of natural and synthetic fibers in polymer matrices.

2. Fiber reinforced polymer matrix composites

Advanced FRP matrix composites (FRPMCs) have high-strength fibers, such as carbon, glass, or aramid, incorporated into a polymer matrix, such as epoxy or polypropylene. These composites are suitable for structural and functional applications because of their high strength-to-weight ratio, stiffness, and durability [11]. Fibers carry weight, while the matrix binds, transports, and protects them from environmental degradation. The fiber orientation, type, and volume fraction allow customization of FRPMCs for particular purposes. The aerospace, automotive, civil engineering, and sports sectors employ these materials for lightweight, corrosion-resistant, and high-performance components. Their applications are increasing owing to manufacturing improvements and sustainable composite solutions [12].

2.1. Overview of polymer matrix composites (PMC's)

PMCs are engineered materials with a polymer matrix reinforced with high-strength fibers or particles for enhanced mechanical, thermal, and chemical capabilities. The polymer matrix, usually epoxy or polyetheretherketone (PEEK), binds and transfers load, whereas the reinforcements, usually carbon, glass, or aramid fibers, offer mechanical strength and stiffness. PMCs' excellent strength-to-weight and stiffness-to-weight ratios of PMCs make them essential for aerospace, automotive, and renewable energy applications that require weight reduction [13]. The polymer matrix provides toughness, environmental resistance, and simplicity of processing, whereas reinforcing fibers may be oriented in precise orientations to adjust anisotropic properties to application needs. The mechanical performance and thermal and chemical resilience of PMCs allow them to be used at severe temperatures or under corrosive conditions. Advanced polymers such as CFRPs have tensile strengths above 3500 MPa and densities as low as 1.6 g/cm³, beating aluminum and steel for weight-sensitive applications [14]. Hand lay-up, filament winding, resin transfer molding, and additive manufacturing offer precise composite architectural control, boosting their utility. Nanofillers, such as graphene and carbon nanotubes, are being added to PMCs to improve their thermal conductivity, electrical characteristics, and damage tolerance. These qualities make PMCs key materials for lightweight, robust, and high-performance engineering solutions [15].

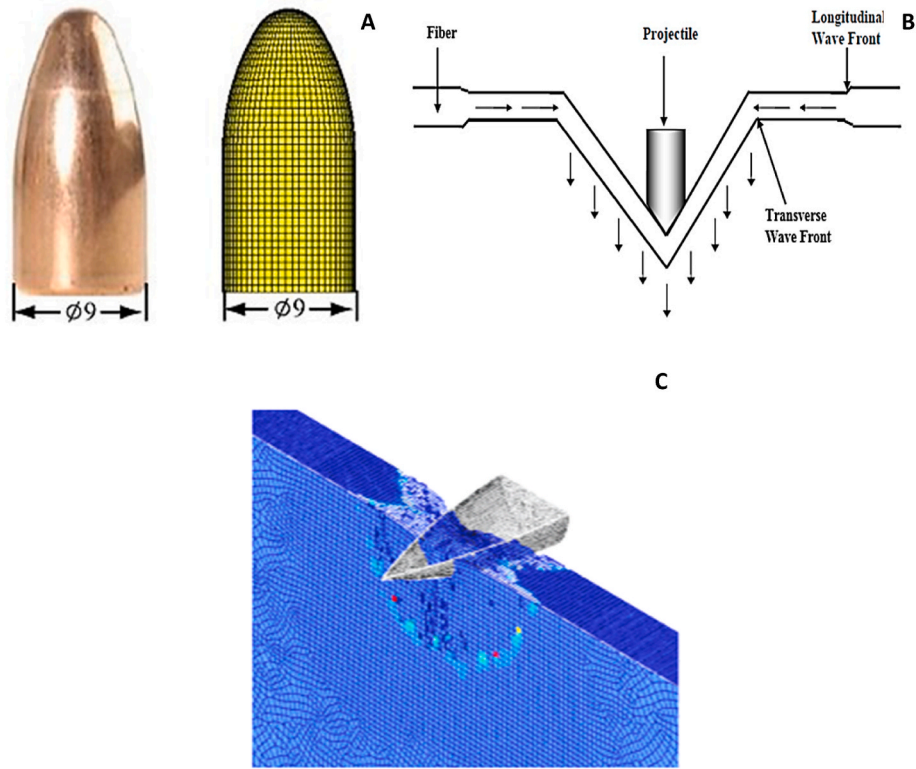


Fig. 1. (a) Bullet shape (Cheeseman et al., 2003) [21], (b) Ballistic mechanism (Benzait et al., 2018) [22], (c) Graphical illustration of projectile impact on the laminate.

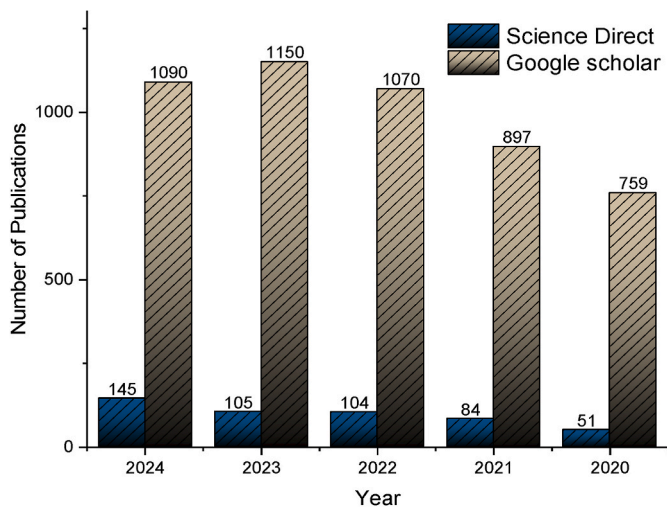


Fig. 2. Ballistics related publications consolidated from various resources.

To increase the strength and defend against ballistic impact, high-performance fibers must be converted into yarns, textiles, or textile reinforcement composites [16,17]. In general, to increase the performance of ballistic targets, several mechanisms should be addressed in addition to the particular features of the fiber. In addition to selecting adequate material characteristics, adding additional layers in different configurations during ballistic panel manufacturing might increase ballistic impact protection [18–20]. More layers improve the ballistic performance, but they typically increase the weight and diminish the flexibility [21–23]. These composites were strong when loaded along the fiber materials. Transverse and longitudinal waves utilized to identify failure modes were created by bullet impact on the composite [24]. The failure types include shear plugging, matrix fracture, and

delamination of absorbed energy [25]. Graphene-reinforced composites improve the mechanical, electrical, and thermal characteristics of polymer, metal, and ceramic matrices. Owing to its high tensile strength (~130 GPa) and Young’s modulus (~1 TPa), graphene is a perfect reinforcement material for stiffness, strength, and fracture toughness. The agglomeration of the graphene nanosheets in the matrix may cause stress concentrations and poor performance. For effective load transmission, graphene surfaces are functionalized to promote matrix-interfacial bonding. High strength and multifunctionality are needed in lightweight structural materials, conductive coatings, and thermal management systems.

Metamaterials are manufactured with features such as negative refractive index, cloaking, or high stiffness-to-density ratios. Their distinct micro- or nano-architectures, rather than chemical makeup, provide them with these capabilities. Mechanical metamaterials employ lattice structures to achieve auxetic behavior (negative Poisson’s ratio) or variable stiffness. Carbon fibers, graphene, and carbon nanotubes are used in hybrid composite systems to maximize synergy. Nanoengineered interfaces, either covalently bonded or interphase-tailored, improve stress transmission and avoid delamination. High-performance aerospace, military, and energy applications demand customized mechanical, thermal, and electromagnetic capabilities of these sophisticated materials. Ceramic composites, such as boron and silicon carbide, are utilized for high-velocity armor plates owing to their hardness and impact resistance.

Multilayer armor systems (MAS) prevent bullet penetration by converting kinetic energy into ballistic absorption processes, including distortion, interface impairment, string stress stretching, delamination, and matrix cracking [26]. Key factors affecting protective material performance include the strength, modulus, elongation at break, projectile deformability, and longitudinal shock wave velocity of the fiber. Due to their strength and lightweight, polymeric-based high-performance fibers including para-aramid (Kevlar®, Twaron®), UHMWPE (Spectra®, Dyneema®), and LCP fibers (Zylon®, Vectran®)

are commonly utilized for ballistic protection in personal and vehicle armor [27].

2.2. Ballistic resistant materials

Considering these benefits, PMCs are vulnerable to high temperatures, ultraviolet (UV) light, radiation, and humidity. Decades in fiber processing and material science research have improved the performance of these fibers for high-performance protective applications [28, 29]. Aramid fibers, debuted in 1961 with Nomex® and subsequently with Kevlar® in 1971, exhibit excellent tensile strength, modulus, and heat, chemical, and wear resistance [30]. Unlike brittle ceramics and glass, aramid fibers are easy to weave and provide lightweight durability, impact resistance, flame retardation, and dimensional stability, making them adaptable for protective and industrial applications [31, 32]. Ultra-high molecular weight polyethylene (UHMWPE) fibers possess high strength and low density. UHMWPE fibers were produced in the 1970s using stirred solutions with a tensile strength of 2.9 GPa and Young's modulus of 101 GPa [30]. Tables 1 and 2 show the mechanical and chemical properties of some of the selected natural and synthetic fibers and polymer matrices, respectively. Fig. 3 shows the various applications of Aramid and UHMWPE fibers in ballistic protection. The modulus and density comparison of various metals, fibers, and polymers, where the polymer and fiber combinations mentioned in the figure show better properties that are almost equal to those of the metal matrix composites (see Fig. 4). The various general fabrication methods of ballistic resistance FRPs are shown in Fig. 5.

Gel spinning technology developed by Dutch State Mines (DSM) and Penning yielded high-strength, high-modulus UHMWPE fibers for commercial manufacturing [33]. After the DSM employed Dyneema® for fibers and composites, Honeywell (formerly Allied Signal) licensed the technology and adopted the brand name Spectra®. UHMWPE fibers are used in ballistic applications, such as woven textiles and composites. Compared to UHMWPE fiber composites, woven fibers exhibit worse ballistic performance owing to their low friction coefficients [34]. Woven UHMWPE textiles are employed for non-ballistic impact applications, whereas composites produced from UHMWPE fibers are used for ballistic applications. The ballistic applications of UHMWPE fiber composites include bullet-resistant vests, helmets, and riot shields for rifle and handgun protection, helicopter armor, and military vehicle roadside bombing protection [35]. The Temperature, humidity, and age affect the ballistic performance of FRP composites. At high humidity, the aramid fibers absorb up to 7 % moisture, reducing the tensile strength and ballistic resistance by 10–15 %. UHMWPE composites absorb 20–30 % less energy beyond 80 °C owing to matrix softening. Extended UV exposure may impair V50 performance by 25 % owing to UV-induced polymer chain scission and hydrolysis. Because synthetic fibers such as aramid and UHMWPE are energy-intensive and carbon-intensive, environmental sustainability is important. Sustainable options, including bio-based fibers (flax and hemp) and recyclable thermoplastic

Table 1
Mechanical Properties Comparison of selected Natural and Synthetic Fibers [26,27].

Major Category	Fiber	Tensile Strength (MPa)	Young's Modulus (GPa)	Elongation at Break (%)	Density (g/cm ³)
Natural Fibers	Cotton Yarn	277–587	5.5–12.6	3–10	1.5
	Jute fiber	383–750	10–30	1.5–1.8	1.3–1.46
	Flax fiber	355–1020	27.6–80	2.7–3.2	1.4
	Hemp fiber	670–11020	30–60	1.6	1.48
	Silk fiber	650–710	10–13	18–25	1.3
	Wool fiber	130–155	2.3–4	25–35	1.3–1.32
	Synthetic Fibers	Nylon	600–1000	2–4	16–25
Polyester		400–1000	10–22	15–30	1.38
Aramid (e.g., Kevlar®)		2400–4100	60–125	2–4	1.44
Polyethylene (UHMWPE, e.g., Dyneema®)		2500–3000	117–130	3–4	0.97
Carbon Fiber		3500–6000	230–600	1–2	1.75–2.0
Glass Fiber		2000–3500	70–90	2.5	2.5

Table 2
Properties of thermoset polymers [38–41].

Property	Epoxy	Vinyl Ester	Polyester
Water absorption (24 h @ 20°C)	0.2–0.4	0.1	0.1–0.3
Density (g/cc)	1.1–1.4	1.2–1.4	1.2–1.5
Izod impact (J/cm)	0.3	2.5	0.15–3.2
Elastic modulus (GPa)	3–6	3.1–3.8	2–4.5
Tensile strength (MPa)	35–100	69–83	40–90
Compressive strength (MPa)	100–200	100	90–250
Elongation (%)	1–6	4–7	2

matrices, provide comparable ballistic performance with decreased environmental effects. Pyrolysis and solvolysis recover high-value carbon fibers from end-of-life composites, thereby solving ballistic performance and sustainability issues [36].

FRPMCs outperformed metals in terms of strength-to-weight ratio. The combination of the high tensile and compressive strengths of carbon or glass fibers with a lightweight polymer matrix results in a structural mass reduction of up to 30 % when compared to that of natural fiber composites [36]. Standardized testing procedures such as NIJ and MIL-STD-662F affect the ballistic performance of FRP composites, but the setups (gas gun vs. powder gun) may alter the V50 and energy absorption measures. Strain-rate effects are essential, with aramid fibers showing a 20–30 % improvement in tensile strength and UHMWPE composites demonstrating increased energy dissipation at high strain rates (10^3 – 10^4 s⁻¹). Ultrasonic testing, thermographic imaging, and acoustic emission monitoring are critical for discovering interior flaws, analyzing damage development, and estimating residual strength without compromising structural integrity. These methods and computer models reveal the material behavior under high-velocity impact, allowing the creation of more dependable and durable composite systems for ballistic applications. Fiber-matrix interfacial bonding improves the shear characteristics and resilience to shear pressures under complicated loading situations [37]. The good thermal and environmental stability of FRPMCs makes them appropriate for harsh operating situations. Thermal performance, including high glass transition and decomposition temperatures, permits aerospace and industrial uses beyond 200 °C, particularly for thermosetting matrices such as epoxy [38]. These composites also outperform metals under hostile circumstances by resisting chemical deterioration, corrosion, and moisture penetration. Protective coatings and surface treatments increase environmental resilience. Innovative FRPMCs with hybrid reinforcements or nanofillers provide long-term stability, mechanical integrity, and dependability for many applications [39,40].

Energy absorption, back-face deformation, and V50 (velocity at which 50 % of the projectile enters) are used to assess the ballistic performance of FRP composites. Aramid fibers (e.g., Kevlar) have V50 values of 400–600 m/s for standard threats, whereas ultra-high-molecular-weight polyethylene (UHMWPE) fibers (e.g., Dyneema) have V50 values of 500–700 m/s owing to their higher specific strength



Fig. 3. Applications of Aramid and UHMWPE fibers in ballistic protection (Open source images) (A) Cut resistance Gloves, (B) Bullet Proof Vests, (C) Tyres, (D) Defence Helmets, (E) Vehicle Armor's, (F) Riot Shields.

and energy dissipation. Although CFRC are stronger, they frequently have lower V50 values ($\sim 300\text{--}500$ m/s) owing to brittle failure modes. Aramid-UHMWPE hybrids have synergistic effects, improving the V50 by 10–15 % above single-fiber systems. Statistical approaches, such as Weibull distribution analysis, forecast penetration probabilities, and improve laminate stacking sequences for energy absorption. Cost-benefit analysis of ballistic FRP composites shows material cost-performance trade-offs. The cost of aramid fibers was approximately \$30. UHMWPE fibers vary from 50 to 80/kg, whereas UHMWP fibers range from 30 to 50/kg.

3. Manufacturing techniques of ballistic resistance materials

FRP production involves creating fiber preforms and reinforcing them with matrix materials in different ways. Fiber preforms are lengthy sheets or mats of weaving, knitting, braiding, and sewing [41–44]. Preforms provide great automation for robots, allowing for fiber angle and content control in each zone of the object to be formed [45].

Prepregs consist of fibers and uncured resin that are pre-impregnated with thermoplastic or thermoset resin and activated with temperature. Cutting and placing the impregnated layers into the open mold makes the prepregs ready to use [47]. Dow Automotive Systems introduced VORAFUSE, a prepreg technology that combines epoxy resin and carbon fiber, to enhance material handling and cycle time in composite compression molding. Collaboration with automobile firms has led to considerable weight reduction, enabling efficient CFRP composite structure manufacturing [48]. The hand lay-up technique is the most prevalent open-mold composite production method. Start by placing fiber preforms in a mold and applying a thin anti-adhesive coat for easy extraction. The resin matrix is poured or brushed onto a reinforcing material, while the roller on the other side forces resin into textiles, enhancing the contact between the reinforcing layers and matrix

materials [49,50]. Spray-up is similar to hand-lay-up, which involves spraying glue and chopped fibers onto a mold using a pistol. A roller was used to simultaneously fuse the fibers into the matrix material. This open mold approach uses chopped fibers for better conformability and quicker lay-up than hand-lay-up [51–53].

In vacuum bag molding, a flexible film composed of nylon polyethylene or polyvinyl alcohol (PVA) is used to seal the component from the outside air. The vacuum bag molding process often involves a hand lay-up. To guarantee fiber infusion into the matrix material, the laminate is first hand-laid and then placed between the vacuum bag and the mold [54,55]. The air between the mold and vacuum bag was removed using a vacuum pump, while ambient pressure compressed the component. Using a vacuum-bagging process, hierarchical composites with multiscale carbon fiber reinforcements were created, resulting in increased flexural and interlaminar shear properties of 15 % and 18 %, respectively [56].

A recent method, called vacuum infusion or vacuum-aided resin transfer molding (VARTM), involves placing preform fibers on a mold and placing a perforated tube between the vacuum bag and resin container. The resin travels through perforated tubes placed over the fiber mat to solidify the laminate structure. This method eliminates extra air in composite structures, making it ideal for larger parts, such as boat hulls and wind turbine blades [57,58]. The surface treatment of natural fibers enhances the strength of textile composites. An alkali-treated flax fiber-reinforced epoxy acrylate resin composite fabricated using the VARTM method improved the tensile strength by 19.7 % [59]. Over the past few decades, various combinations of matrices and reinforcement materials have been used by various researchers, and the outcomes of this research are presented in Table 3. To incorporate a full cost evaluation of FRP composite manufacturing methods, such as autoclave curing, resin transfer molding (RTM), and compression molding, which differ in capital investment and output rates. For instance, autoclave

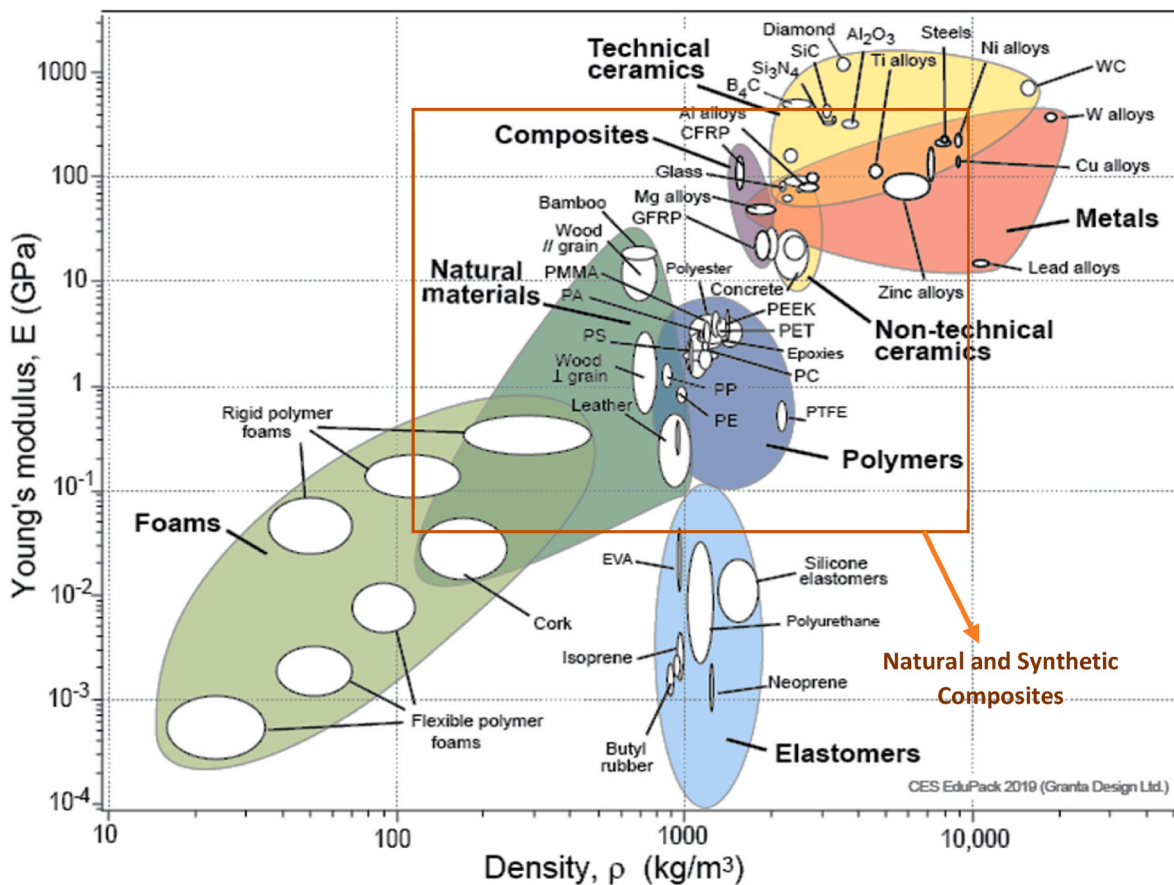


Fig. 4. Representation of Fibers and Polymers - Ashby Chart (Open access).

curing produces high-quality laminates, but costs \$50–100/kg, whereas RTM costs \$20–40/kg with greater scalability. Lifecycle cost studies, including raw material prices (aramid at \$30–50/kg, UHMWPE at \$50–80/kg), maintenance, and end-of-life recycling, may balance initial expenditures by 20–30 % via weight reductions and durability. This complete economic review will balance performance, manufacturing scalability, and lifetime economics to determine the military feasibility [59].

Numerous studies have been conducted on integrating nanomaterials, such as CNTs, graphene, and nanoclays, with FRP composites to improve their mechanical, thermal, and ballistic characteristics. Graphene oxide (GO) in epoxy matrices improves interfacial bonding with carbon fibers, boosting interlaminar shear strength by 20–30 % and fracture toughness by 40–50 %. Owing to the stress transfer and fracture bridging processes, adding CNTs (0.5–2 wt%) to UHMWPE composites improves energy absorption by 15–25 % under high-velocity impact. Nanoclays distributed in aramid-based composites limit the moisture absorption by 50 %, preventing deterioration under humid conditions. Electrophoretic deposition (EPD) and layer-by-layer (LbL) assembly provide fine nanomaterial distribution control and enhanced performance. These advances demonstrate that nanomaterial-enhanced FRPs have superior strength, endurance, and multifunctionality for next-generation ballistic applications. Precise and fast composite component fabrication is possible using injection molding. Fiber composite pellets are fed into a hopper and carried by a heated barrel screw in a typical injection-molding process. Once melted in a barrel, the screw injects the material via a nozzle into the mold, where it cools and forms [60]. The medical sector benefits from injection molding for the thermoplastic encapsulation of electrical equipment [61]. Surface treatments improve the fiber-matrix compatibility and uniform fiber dispersion in biocomposites [62]. Similarly, the pultrusion method

involves pulling continuous fibers through a resin fluid and consolidating them in a heated die. It is a continuous technique for making composites with a consistent cross-section and longer length, enabling great automation and reducing production costs [63–65]. Different composite fabrication methods exhibit unique characteristics in fiber laminates, influence their properties, and are preferred for selective applications. The typical layouts of some of the significant fabrication methods are shown in Fig. 6.

4. Mechanism of ballistic impact

The material characteristics, impact dynamics, and energy dissipation mechanisms interact to cause a ballistic impact on fiber-reinforced PMCs. A high-velocity bullet impacts the composite material, transferring kinetic energy rapidly and causing many deformation and failure mechanisms in the fiber and matrix structure [93,94]. The initial projectile contact causes localized stress that compresses, shears, and bends the fibers in the impact zone. Fiber breakage, matrix cracking, and delamination result from the outward spreading of the stress. Reinforcing fibers, especially those in the impact force direction, resist penetration, while the polymer matrix distributes and dissipates energy throughout the composite structure [95,96].

Further matrix cracking, fiber pull-out, and debonding between the fibers and the matrix material occur as the bullet penetrates the composite. Energy absorption is increased by frictional forces and impact energy dissipation across a greater surface. Delamination allows energy to spread via the interlaminar layers, limiting the possibility of full penetration [97–99]. Fiber rupture and matrix shear failure often occur along the projectile path. Energy absorption and resistance depend on the fiber type, orientation, matrix characteristics, and composite thickness. These processes provide FRC with exceptional impact resistance,

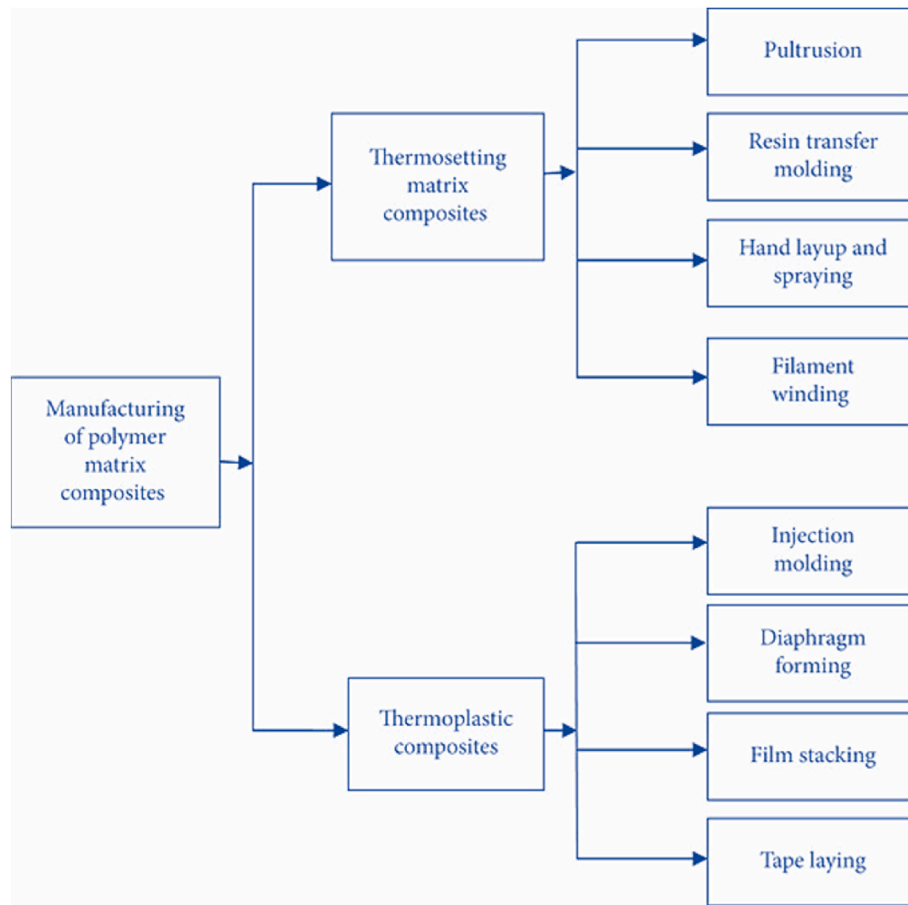


Fig. 5. General Fabrication methods of Ballistic Resistance FRPs (Dhanasekar et al., 2022) [46].

limited projectile speed, and back face deformation, making them ideal for armor and structural barriers [100]. Fig. 7 depicts the mechanism of ballistic impact and its induced strain in the fiber laminate.

The materials, shapes, and projectiles mostly affect the FRPC ballistic impact response. Understanding the material reaction to ballistic impact is challenging. The complexity increases with the impact velocity, projectile shape, manufacturing technology, matrix composition, and reinforcement [101]. Limited research exists on the ballistic performance of natural hybrid composites, owing to their complexity. Material reactions to ballistic impacts are both local and global [102]. The velocity of the bullet determines the local and global reactions of the material to the ballistic impact. Damaged target plates may encounter several modes, such as fiber tensile failure, shearing, matrix cracking, indentation, and delamination. The prevalence of these failure modes depends on the material quality, impact velocity, projectile shape, and target [103]. Low-velocity impact events [104] favor global energy-absorbing systems owing to the ample time required for energy transfer and dissemination across a vast region. The local reaction of the target material is its behavior at the projectile contact point [105]. Fig. 8 depicts the various projectiles and their nose angles used for the ballistic impact testing.

Impact loading depends on the projectile impact angle because it affects the stress distribution and intensity in the FRP composite, thereby altering energy absorption and penetration resistance [108, 109]. The power of a projectile hitting at a 90-degree angle is concentrated in a compact region, boosting the stress and penetration. However, when the angle of contact decreases (becoming more oblique), the bullet hits a greater surface area, redirecting some of the force along the plane of the composite [110]. In a numerical manner, the ballistic limit velocity of a material with a 50 % chance of penetration can be

calculated using Equation (1).

$$V_{50} = (2 \times E / \rho) \text{-----} \quad (1)$$

Where:

V_{50} = ballistic limit velocity (m/s)

E = energy absorption per unit area (J/m^2)

ρ = areal density of the material (kg/m^2), calculated as mass per unit area.

This oblique impact increases the fiber pull-out, delamination, and matrix cracking by dissipating the force over a larger region, boosting the energy absorption without complete penetration. Angled impacts may increase interlayer shearing and debonding, increasing energy dissipation owing to the layered structure and fiber orientation of the composite [111].

5. Failure mechanism of the hybrid composites to ballistic impacts

The failure criteria in Hashin's [113] study of UD fiber composites were adapted from Chang and Lessard's [114] elastic stiffness degradation models. When studying composite materials, intralaminar failure modes, such as matrix cracking, fiber-matrix shear failure, and fiber failure, have been studied. The Fig. 9 shows typical intra-laminar and inter-laminar failure modes of fiber composites. Failure modes in composite laminates are characterized using in-plane (1–2) and out-of-plane (2–3 plane) shear modes. Most impact experiments focus on intra-laminar failure mechanisms, such as fiber breaking, transverse tensile failure, matrix in-plane shear, and matrix out-of-plane shear. However, the transverse compressive failure mode, which is less common, must be addressed in most models. Puck et al. [115,116] suggest

Table 3
Prior art research on various matrix and reinforcement materials

Reference	Polymer Matrix	Fiber Material	Fabrication Technique	Research Outcome
[67]	Polylactic acid	Hemp Fiber	Compression Molding	Improved mechanical properties Low moisture absorption
[67]	Epoxy resin	Hemp Fiber	Compression Molding	Improved mechanical properties Low moisture absorption
[68]	PVA217 resin	Bamboo Fiber	Press Molding	Improved Fracture strain (1.25 %)
[69]	Polyester resin	TD4 Jute	Hand Layup Molding	Improved Tensile strength (135.6 MPa)
[70]	Green epoxy resin	Bast Flax	Vacuum-assisted resin transfer Molding	Improved tensile strength and modulus
[71]	High-density polyethylene	Hemp Fiber	Injection Molding	Improved Flexural strength (41.6 MPa)
[72]	Bisphenol A epoxy resin	Carbon/E-glass	Hand Layup Molding	Improved Storage modulus (854.6 MPa)
[73]	LY556 epoxy resin	Glass/Carbon	Hand Layup Molding	Improved Interlaminar shear strength (39 MPa)
[74]	DER331 epoxy resin	Oil palm/Kenaf	Hand Layup Molding	Improved tensile and flexural strength
[75]	LY556 epoxy resin	Carbon/Flax	Hand Layup Molding	Improved Hardness (70.85 HRC)
[76]	Vinyl ester	Glass/Jute	Hand Layup Molding	Improved Impact strength (1.9J)
[76]	polyester	Glass/Jute	Hand Layup Molding	Improved Hardness (64 HRL)
[77]	LH285 epoxy resin	Vectran/Aramid	Hot Pressing	Improved Bending strength (400 MPa)
[77]	LH285 epoxy resin	Vectran/Carbon	Hot Pressing	Improved Young's modulus (47 GPa)
[78]	LY556 epoxy resin	E-Glass	Hand Layup Molding	Improved mechanical Properties
[79]	Poly Lactic Acid (PLA)	HDPE	Additive Manufacturing	Improved thermal properties
[80]	Phenolic Resin	E-Glass	Hand Layup Molding	Improved Fire performance
[81]	LY556 epoxy resin	Carbon	Hand Layup Molding	Improved corrosion resistance

that fracture angles may range from 0 to 55°, depending on multiaxial load. Experimental research on transversely impacted composite structures often mentions four failure modes: fiber breaking, transverse tensile failure, matrix in-plane failure, and out-of-plane shear failure [117, 118].

In the last five decades, numerous intralaminar failure criteria for composites have been proposed. Worldwide, failure exercises have been used to evaluate some of these causes. Most criteria fail to capture certain patterns in the experimental failure envelopes. Although the exercise identified interesting failure theories and criteria, few are currently practicable for checking laminate strength in non-progressive failure analysis [119]. Commercial software was used to examine the progressive failure of the laminate using the following failure criteria as

damage-start criteria [120]: Commonly used failure criteria include the maximum stress or strain [121], Tsai-Hill and Tsai-Wu [122,123], Hashin [124], and Larc [125,126]. Each failure criterion has distinct operating conditions that can reliably predict failure. Fig. 10 depicts the typical step-by-step procedure of the two-stage laminate destruction process owing to the high-velocity ballistic projectile.

Fig. 10 shows how a projectile destroys the laminate where the first-step projectile enters the laminate's outer layers, generating a localized deformation zone where the material absorbs energy and cracks around the impact. The second stage demonstrates how the energy disperses further into the laminate, producing delamination and fracture. Shock-waves and debris discharge material from the collision site. Deformation, energy absorption, and fracture occur when the laminate fails under ballistic impact.

6. Ballistic behaviour testing methods

FRP must be tested for their ballistic performance under high-velocity impacts in military, aerospace, and automotive applications. Fiber-reinforced polymers (FRPs) are ideal for ballistic-resistant armor and structural applications owing to their high strength-to-weight ratio, flexibility, and energy dissipation [82,83]. Ballistic impact testing evaluates the ability of such materials to absorb and disperse kinetic energy upon impact, thereby preventing penetration and disintegration. Standard testing simulates real-world ballistic impacts and examines composite damage progression, delamination, and fiber breaking [84]. High-velocity projectile tests, drop-weight tests, and specialist tests, such as the V50 ballistic limit test, determine the susceptible penetration velocity of the composite material [85]. These approaches allow engineers and researchers to assess the energy absorption, damage tolerance, and impact strength. Material scientists can optimize composite fiber types, orientations, and matrix materials for ballistic resistance by studying these features.

Advanced ballistic testing procedures provide safer, lighter, and more durable impact-resistant materials for achieving structural integrity and occupant safety [86,87]. ASTM D7136/D7136M – 15 is a standardized test technique for testing the FRP composite damage resistance under drop-weight impact, providing vital data on the residual strength and damage area. As per the NATO standard STANAG 2920, personal armor and vehicle protection were tested using V50 (velocity at 50 % penetration probability) and fragment-simulating projectiles (FSPs) to assess material performance against high-velocity threats. The National Institute of Justice created the NIJ Standard-0101.04 to categorize ballistic-resistant body armor based on penetrating resistance and back-face deformation against different projectile types. The ballistic performance, durability, and dependability of both military and civilian FRP composites were assessed using these criteria, guaranteeing a uniform and comparable assessment across industries.

Charpy impact testing measures the energy of a material absorbed during fracture when hit by a weighted pendulum, and assesses toughness and shock resistance. A notched specimen was held horizontally and shattered using a pendulum in the Charpy test. ASTM D6110 standard used in Charpy impact testing to assess polymer composite and plastic material impact resistance. Energy-absorbed data assist in determining the appropriateness of impact-resistant materials [88]. While Charpy used a pendulum, Izod used a vertically clamped specimen hit at one end to determine the impact resistance. The toughness and ductility of the composite were measured by its energy absorption before breakage. The polymer composite Izod impact test followed ASTM D256. Polymer composites are often tested using the Izod test, which reveals their behavior under an abrupt force that is critical for high-impact applications [89].

In drop impact testing, a weighted striker is dropped from a defined height onto a specimen to evaluate the energy required to fracture or damage it. This test simulated real-world impacts better than pendulum testing by directly loading the material. This determines the energy

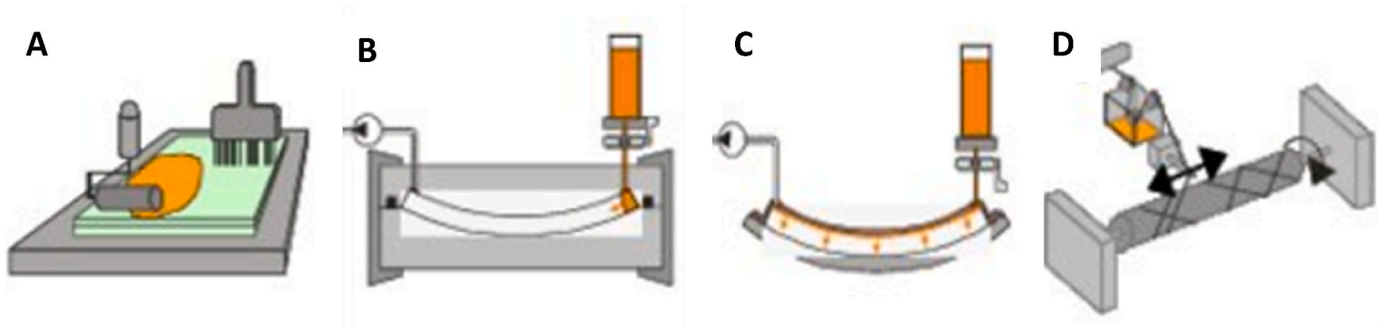


Fig. 6. Typical layouts of Some of the Significant Fabrication Methods (Mahrholz et al., 2003) [66] (A) Hand Layup method, (B) Resin Transfer, (C) Resin Infusion, (D) Filament winding.

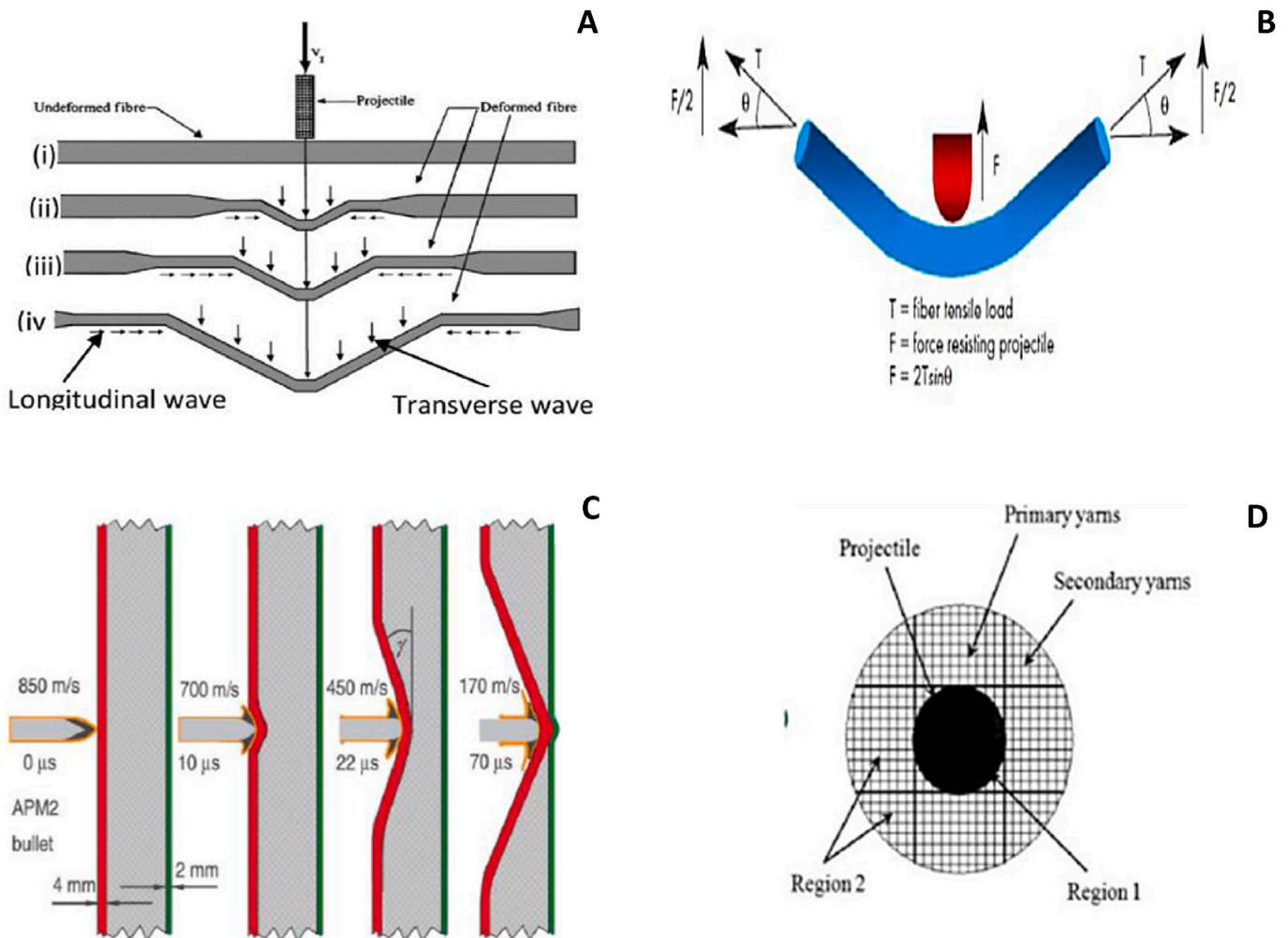


Fig. 7. Bullet penetration mechanism (A) Yarn (Naik et al., 2005) [106], (B) Composite (Abteew et al., 2019) [107], (C) Energy absorption (Abteew et al., 2019) [107], (D) Impact Region – Front View [107] (Abteew et al., 2019).

threshold for cracking and deformation. ASTM D7136 measures the drop weight impact damage resistance of PMC's [90]. This test determines material durability in automotive, aerospace, and construction applications. In puncture impact testing, a probe or striker is used to penetrate a specimen and determine its penetration resistance. Materials subjected to sharp and focused pressures benefit the most.

A probe or puncture instrument is dropped or driven into the material to assess toughness and puncture resistance. Standard ASTM D3763 is used for high-speed puncture impact testing of plastics, including polymer composites. Packaging, protective gears, and other

puncture-resistant applications utilize this test to anticipate material performance [91]. Table 4 presents some of the most commonly used test standards for ballistic testing referred by the University of Dayton Research Institute. Fig. 11 depicts the typical test setup for the ballistic impact testing of PMCs, which was established by the National Institute of Justice (NIJ).

Gun ballistic testing assesses the capacity of materials such as FRP's to resist high-velocity bullets. This test mimics bullet impacts to evaluate armor, vehicle panels, and other defensive applications. The armed forces, security forces, and protective gear safety depend on penetration

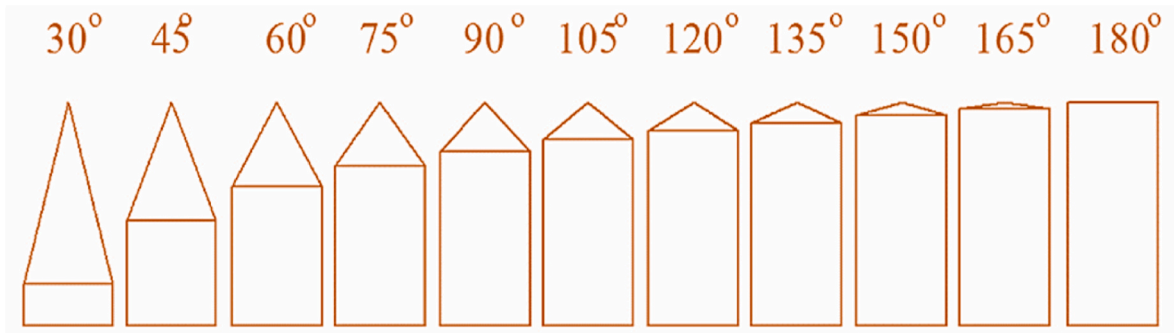


Fig. 8. Ballistic impact testing - Projectile and its nose angles (Talebi et al., 2008) [112].

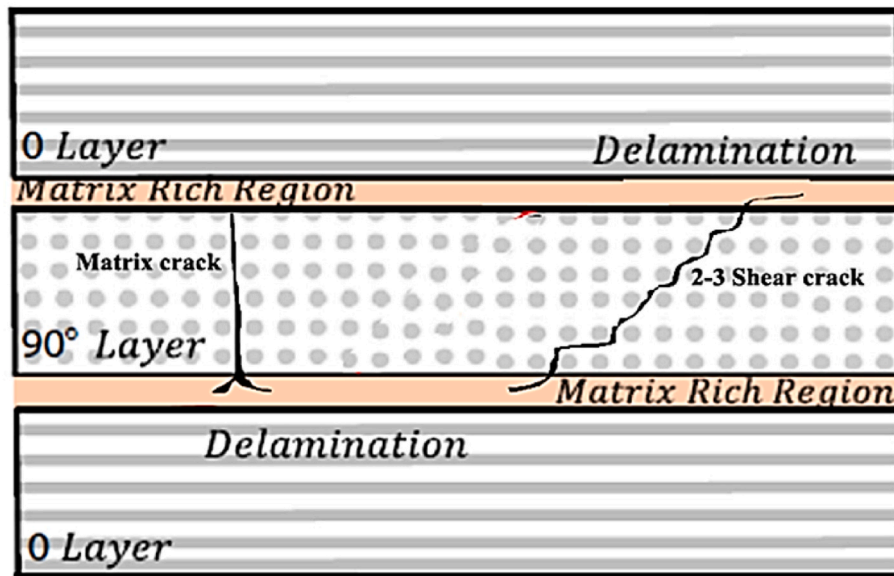


Fig. 9. Intra-laminar and inter-laminar failure modes [127] (From open access publication).

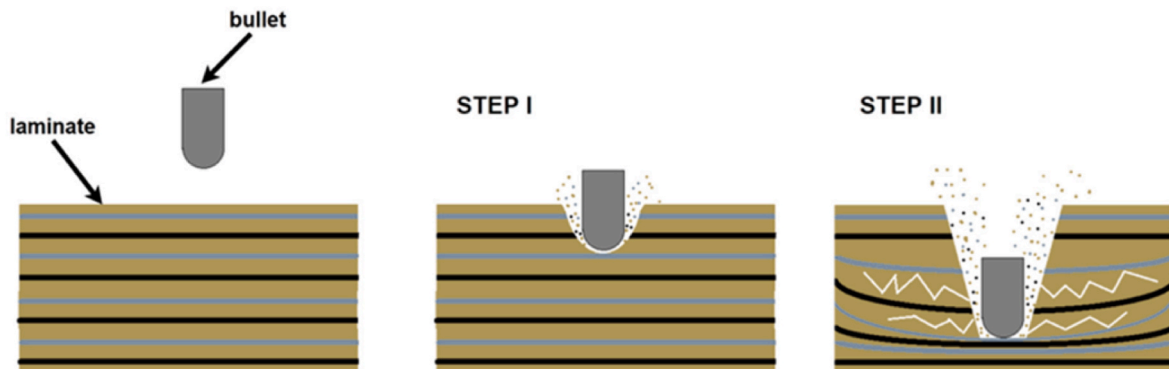


Fig. 10. Step by step laminate destruction process [128] (From open access publication).

resistance, energy absorption, and impact deformation [92]. The test configuration, projectile types, and permissible penetration or blackface deformation were standardized in NIJ Standard 0101.06 for personal body armor and MIL-STD-662F for ballistic resistance. These standards allow producers and researchers to compare and certify ballistic protection materials in terms of consistency and reliability. Based on the proposed applications and materials, different testing methods were used to characterize the composites.

7. High performance FRPMCs for defence armours

Future defense technologies will leverage AI to improve computational military thinking and revolutionize intelligence, surveillance, and reconnaissance (ISR) operations. Military systems can quickly digest information, thereby improving situational awareness and force protection. Hypersonic flights, directed energy weapons, and space militarization are being investigated to equip defense systems for current threats. These developments attempt to lessen soldiers' cognitive and

Table 4
Ballistic impact test standards

Standard	Description
ASTM F 1233	Security Glazing Materials
EN 1522	Bulletproof Classifications
NIJ-STD-0108.01	Ballistic Resistant Protective Materials
AEP-55 (NATO)	Protection Levels for Light Armoured Vehicles
STANAG 4569	Protection Levels of Light Armoured Vehicles
SD-STD-01.01	Department of State Ballistic Resistance of Structure Systems
MIL-PRF-46103	Armor: Lightweight, Composite
MIL-STD-3038	Ballistic Defeat Materials

physical strain and increase mobility in challenging terrains. Robotics and Autonomous Systems (RAS) improve operational efficiency and decision-making for defense forces, helping them govern territory and protect civilians.

The Internet of Things (IoT) is upgrading defense by linking ships, planes, tanks, drones, soldiers, and bases to exchange information and react quickly to threats. The networked method increases cognition, field knowledge, awareness, and response speed, providing forces at the edge under complicated operating circumstances. Lightweight materials and 3D printing minimize military equipment weight, fuel consumption, and resource use, enabling quicker, more flexible deployments. Big data analytics helps armed forces make strategic decisions and respond to threats more quickly by identifying crucial trends in massive datasets.

Hybrid methods combining aramid fibers with shear-thickening fluids (STFs) and optimized fiber arrangements have improved FRP armor designs. Aramid fibers, rich in tensile strength (~3 GPa) and energy absorption, are typically combined with STF-impregnated textiles, which build viscosity rapidly at high strain rates, increasing the impact resistance by up to 30%. UD, cross-ply, and angle-ply fiber arrangements optimized the stress distribution and energy dissipation. A 0°/90° cross-ply configuration enhances the multi-axial impact resistance, whereas angled orientations increase the shear strength. These hybrid systems and advanced manufacturing methods, such as vacuum-assisted resin transfer molding (VARTM), create lightweight, high-performance armours with superior ballistic protection and multi-hit capabilities for military and civilian use.

Owing to their endurance and adaptability, lightweight materials such as CFRP and GRP are increasingly crucial in military applications. Military aircraft, UAVs, naval ships, and other defence equipment employ these materials for corrosion resistance, thermal insulation, and damage mitigation. Nanotechnology in lightweight materials and self-healing carbon fiber composites enables intelligent and robust systems. The military industry is also upgrading its personal protection equipment with lightweight ballistic materials to make ground

personnel safer and more comfortable. The high prices and recyclability difficulties of lightweight materials remain hurdles; however, research is underway to improve material integration in military applications. Fig. 12 depicts the future global market reports of armour materials.

On the other hand, modern body armor protects against many dangers, but its limits remain. Current armor systems protect the body from high-velocity rifle bullets; however, they typically make the face, neck, and extremities susceptible. Soft armor-like aramid fibers defend against explosive fragmentation and lower-velocity threats but not high-velocity projectiles. Soldiers may suffer traumatic brain injuries due to explosion overpressure even when wearing helmets. Researchers are investigating modular helmets with full-face shields to protect troops from blast waves and to reduce blast-related brain damage by 80%. The body armor is made of ceramic plates, aramid fibers, or polyethylene, depending on the protection required.

E-type armor, composed of ceramic, polyethylene, and aramid layers, can survive several rifle bullets. Materials that minimize armour weight without reducing protection are being researched to improve military comfort and mobility. As ballistic protection increases, boron carbide is the preferred material for high-grade armor, owing to its hardness and low density. The high production cost and brittleness of ceramics hinder the improvement of armour systems. Nacre, or "mother of pearl," has a LEGO-like structure that makes it impact-resistant. The U.S. The Army Research Lab mixes ultrahigh molecular weight polyethylene (UHMWPE) with silica nanoparticles to create a stronger, lighter armour material than steel. High thermal conductivity allows this material to disperse heat and absorb kinetic energy, making it excellent for use in body armor, helmets, and vehicle protection. These

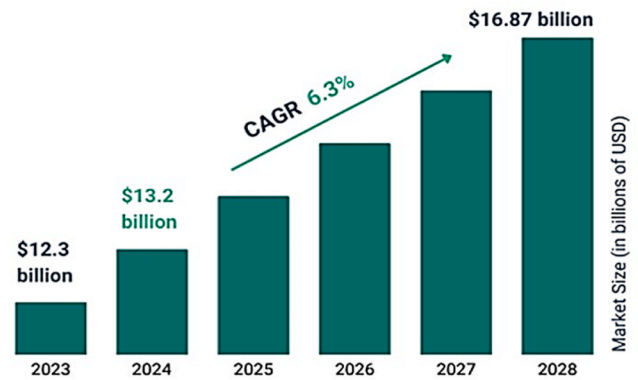


Fig. 12. Armour material global market report (Company, T. B. R. (n.d.). Armor materials market report 2024) [129].

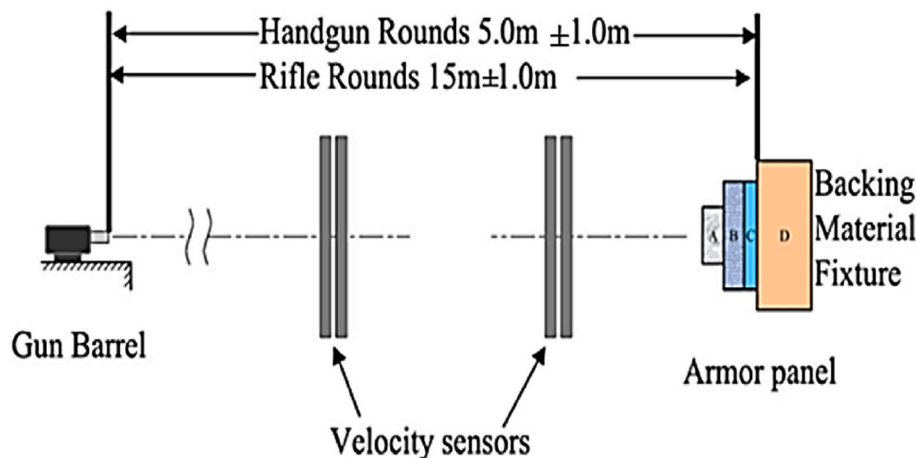


Fig. 11. Ballistic test setup and range illustration (National Institute of Justice, standard) [82].

advances might provide stronger, lighter, and more military-adaptable armours.

The limited coverage and significant weight of modern body armor are mostly due to the use of strong ceramic materials. Soldiers and vehicle armor are typically made of ceramics, metals, or FRC to resist deformation and absorb energy. Recent U.S. Army proposed that carbon-nanotube-infused polymers may improve energy dissipation and solve these issues. This polymer research indicates that these new materials are lightweight, corrosion-resistant, and electrically conductive, making them suitable for personal protective gears and vehicle armor. These carbon nanotube-infused polymers may protect military vehicles against static conditions, discharge, and lightning. The conductive nature of these materials may allow real-time structural health monitoring using embedded strain and damage sensors in army helicopters, which experience tremendous vibration and wear. This idea may improve vehicle safety by accurately assessing component lifespan. Drexel University researchers are currently investigating 3D printing using these polymers to broaden their applications. This study is currently theoretical and modeling; however, future army team partnerships should enable real-world testing and incorporation into combat vehicles.

Chinese researchers have created "golden silk," a lightweight, heat-resistant, and corrosion-resistant para-aramid fiber, for military and civilian use. This Kevlar-like fabric was developed by state-owned Sinopec over 16 years for use in body armor, precise instruments, and military equipment. The 1.5-kg "golden silk" body armor blocks machine gun fire and disperses energy better than bullets and debris. The material strengthens and endures extreme circumstances, making it useful for vehicles, ships, planes, rockets, and personal protection. China's military and defense companies may now buy locally created high-performance fibers instead of imported fibers, which were previously limited and expensive. New 3D printing technology might allow the U.S. military to create personalized body armor in the field, avoiding supply lines. The Army Research Laboratory (ARL) is a 3D printing method for high-density ceramics for body armor, inspired by abalone shells. This might lead to lighter and harder armor that shatters projectiles, protecting soldiers from bullets and shrapnel. Units may swiftly produce custom-fitted armor by 3D printing on-site, eliminating the logistical issues of delivering different armor sizes and lowering waste. This method may improve the availability of remote soldier armor [130]. Similarly, FRP waste must be recycled and reused for sustainability via mechanical recycling, pyrolysis, and solvolysis. Mechanical recycling shreds and grinds FRPs into fillers or reinforcements for new composites, reducing fiber length and mechanical characteristics. Solvolysis dissolves the polymer matrix and separates the carbon fibers using chemical solvents, whereas pyrolysis thermally decomposes the polymer matrix at 400–700 °C to recover carbon fibers with up to 90 % of their original strength. New processes, such as microwave-assisted pyrolysis and enzymatic recycling, save energy and are environmentally benign. These methods recover high-value materials, decrease waste, and encourage circular-economy FRP applications [131].

8. Conclusions

Advanced defensive armor materials meet the demand for enhanced protection, durability, and adaptability while lowering the weight and bulk. CFRP and GRP are lightweight, high-strength composites that improve troop mobility and comfort, while boosting ballistic protection. In addition, self-healing composites, sophisticated ceramics, and natural or synthetic fiber-reinforced polymers allow armor systems to resist harsh environments and absorb impact. Such materials may be used for body armor, vehicles, and aircraft protection owing to their complex shapes and structures. This study emphasizes the need for a holistic approach that includes manufacturing, characterization, and current developments to understand ballistic resistant materials. Defense armor development must include environmental and economic factors for sustainability. Lifecycle studies of raw materials, cost-effectiveness in

large-scale applications, and sustainable resource use are developing this discipline. Additive manufacturing and hybrid material processing streamline production and customization. Future trends include merging AI and IoT to create intelligent armor systems that can detect and respond to threats in real-time. Nanocomposites and bio-inspired constructions promise to raise the protection and resilience requirements. To overcome these hurdles and capitalize on innovation, composite development must include cross-disciplinary cooperation and research on lightweight, versatile, and adaptable materials. As global threats evolve, the defense industry must combine performance, sustainability, and affordability to offer effective and deployable armour systems.

The future of FRP defense materials depends on the material science, production, and AI-driven design. Large-scale graphene-carbon nanotube nanocomposites will improve strength, durability, and multifunctionality. However, high expenses, recycling, and sustainability remain as issues. Bio-based resins and recyclable thermoplastics have become increasingly popular. IoT-integrated real-time structural health monitoring (SHM) improves predictive maintenance and safety. Defence agencies must produce lightweight, intelligent, and novel composite materials for next-generation military applications to optimize their performance, cost efficiency, and sustainability.

CRedit authorship contribution statement

Nilesh S. Gaikwad: Writing – original draft, Investigation, Formal analysis, Data curation, Conceptualization. **Dhiraj D. Deshmukh:** Writing – review & editing, Supervision, Software, Resources, Data curation, Conceptualization. **Sachin P. Kakade:** Visualization, Resources, Formal analysis, Data curation.

Declaration of competing interest

The authors declare that they have no conflicts of interest related to the research, authorship, or publication of this review article. The study is based on publicly available data and does not involve any proprietary technologies or affiliations that could influence the findings or interpretations presented.

References

- [1] G. Czel, Wisnom, Demonstration of pseudo-ductility in high performance glass/epoxy composites by hybridisation with thin-ply carbon prepreg, *Composites Part A Applied Science and Manufacturing* 52 (2013) 23–30, <https://doi.org/10.1016/j.compositesa.2013.04.006>.
- [2] P. Feraboli, K.T. Kedward, Enhanced evaluation of the low-velocity impact response of composite plates, *AIAA J.* 42 (10) (2004) 2143–2152, <https://doi.org/10.2514/1.4534>.
- [3] M. Karahan, K. Yildirim, Low Velocity Impact Behaviour of Aramid and UHMWPE Composites. *Fibres and Textiles in Eastern Europe* 23 (111) (2015) 97–105, <https://doi.org/10.5604/12303666.1152522>, 3.
- [4] S. Khatiwada, C.A. Armada, E.V. Barrera, Hypervelocity impact experiments on epoxy/ultra-high molecular weight polyethylene fiber composites reinforced with single-walled carbon nanotubes, *Procedia Eng.* 58 (2013) 4–10, <https://doi.org/10.1016/j.proeng.2013.05.003>.
- [5] R. Kurahatti, A. Surendranathan, S. Kori, N. Singh, A. Kumar, S. Srivastava, Defence applications of polymer nanocomposites, *Def. Sci. J.* 60 (5) (2010) 551–563, <https://doi.org/10.14429/dsj.60.578>.
- [6] S. Lee, G. Kim, S.J. Kim, C. Chang, High-energy impact behaviors of hybrid composite plates strengthened with 3D-UHMWPE composites, *Shock Vib.* 2018 (2018) 1–11, <https://doi.org/10.1155/2018/7626075>.
- [7] N. Naik, Y.C. Sekher, S. Meduri, Damage in woven-fabric composites subjected to low-velocity impact, *Compos. Sci. Technol.* 60 (5) (2000) 731–744, [https://doi.org/10.1016/s0266-3538\(99\)00183-9](https://doi.org/10.1016/s0266-3538(99)00183-9).
- [8] L. Natrayan, M.S. Santhosh, Effect of Pineapple/Coconut sheath fiber reinforced with polyester resin matrix on mechanical and microstructure properties of hybrid polyester composite, in: *Springer Proceedings in Materials*, 2020, pp. 315–323, https://doi.org/10.1007/978-981-15-6267-9_37.
- [9] R. Sasikumar, E. Natarajan, E-Glass/phenolic matrix/APP laminate as a potential candidate for battery casing of e-vehicle - experimental investigations, *Mater. Res. Express* 8 (4) (2021) 045310, <https://doi.org/10.1088/2053-1591/abf8e5>.
- [10] R. Sasikumar, S.D.A. Khadar, L. Natrayan, Ammonium polyphosphate reinforced E-glass/phenolic hybrid composites for primary E-vehicle battery casings – A study on fire performance, *J. N. Mater. Electrochem. Syst.* 24 (1) (2021) 247–253, <https://doi.org/10.14447/jnmes.v24i4.a03>.

- [11] W.P. Schonberg, Protecting Earth-orbiting spacecraft against micro-meteoroid/orbital debris impact damage using composite structural systems and materials: an overview, *Adv. Space Res.* 45 (6) (2009) 709–720, <https://doi.org/10.1016/j.asr.2009.11.014>.
- [12] M. Shamsuyeva, O. Hansen, H. Endres, Review on hybrid carbon/flax composites and their properties, *International Journal of Polymer Science* (2019) 1–17, <https://doi.org/10.1155/2019/9624670>, 2019.
- [13] B. Shivamurthy, K.U. Bhat, S. Anandhan, Mechanical and sliding wear properties of multi-layered laminates from glass fabric/graphite/epoxy composites, *Mater. Des.* 44 (2012) 136–143, <https://doi.org/10.1016/j.matdes.2012.07.059>, 1980–2015.
- [14] Y. Swolfs, L. Gorbatikh, I. Verpoest, Fibre hybridisation in polymer composites: a review, *Composites Part A Applied Science and Manufacturing* 67 (2014) 181–200, <https://doi.org/10.1016/j.compositesa.2014.08.027>.
- [15] Z.S. Wu, C.Q. Yang, Y.H. Tobe, L.P. Ye, T. Harada, Electrical and mechanical characterization of hybrid CFRP sheets, *J. Compos. Mater.* 40 (3) (2005) 227–244, <https://doi.org/10.1177/0021998305053452>.
- [16] M.R.M. Asyraf, M.R. Ishak, S.M. Sapuan, N. Yidris, Utilization of bracing arms as additional reinforcement in pultruded glass fiber-reinforced polymer composite cross-arms: creep experimental and numerical analyses, *Polymers* 13 (4) (2021) 620, <https://doi.org/10.3390/polym13040620>.
- [17] M. Ishak Asyraf, S. Sapuan, N. Yidris, Conceptual design of creep testing rig for full-scale cross arm using TRIZ-Morphological chart-analytic network process technique, *J. Mater. Res. Technol.* 8 (6) (2019) 5647–5658, <https://doi.org/10.1016/j.jmrt.2019.09.033>.
- [18] R. Ilyas, S. Sapuan, N.M. Nurazzi, M.N.F. Norrahim, R. Ibrahim, M. Atikah, M. Huzaifah, A. Radzi, S. Izwan, A.N. Azammi, R. Jumaidin, Z. Ainun, A. Atiqah, M. Asyraf, L. Kian, C. Hassan, Macro to Nanoscale Natural Fiber Composites for Automotive Components: Research, Development, and Application, Elsevier eBooks, 2021, pp. 51–105, <https://doi.org/10.1016/b978-0-12-820559-4.00003-1>.
- [19] L. Wang, S. Kanesalingam, R. Nayak, R. Padhye, Recent trends in ballistic protection, *Textiles and Light Industrial Science and Technology* 3 (0) (2014) 37, <https://doi.org/10.14355/tlist.2014.03.007>.
- [20] Z. Cai, Z. Li, J. Dong, Z. Mao, L. Wang, C.J. Xian, A study on protective performance of bullet-proof helmet under impact loading, *Journal of Vibroengineering* 18 (4) (2016) 2495–2507, <https://doi.org/10.21595/jve.2015.16497>.
- [21] B.A. Cheeseman, T.A. Bogetti, Ballistic impact into fabric and compliant composite laminates, *Compos. Struct.* 61 (1–2) (2003) 161–173, [https://doi.org/10.1016/s0263-8223\(03\)00029-1](https://doi.org/10.1016/s0263-8223(03)00029-1).
- [22] Z. Benzait, L. Trabzon, A review of recent research on materials used in polymer–matrix composites for body armor application, *J. Compos. Mater.* 52 (23) (2018) 3241–3263, <https://doi.org/10.1177/0021998318764002>.
- [23] A.H. Elkarem, A study on Dyneema fabric for soft body armor, *International Journal of Engineering Applied Sciences and Technology* 5 (2) (2020) 115–118, <https://doi.org/10.33564/ijeast.2020.v05i02.016>.
- [24] A. Bhatnagar, *Lightweight Ballistic Composites*, Elsevier eBooks, 2016, <https://doi.org/10.1016/c2014-0-03657-x>.
- [25] H. Pang, L. Xu, D. Yan, Z. Li, Conductive polymer composites with segregated structures, *Prog. Polym. Sci.* 39 (11) (2014) 1908–1933, <https://doi.org/10.1016/j.progpolymsci.2014.07.007>.
- [26] V. Mahesh, S. Joladarashi, S.M. Kulkarni, Comparative study on ballistic impact response of neat fabric, compliant, hybrid compliant and stiff composite, *Thin-Walled Struct.* 165 (2021) 107986, <https://doi.org/10.1016/j.tws.2021.107986>.
- [27] W.E. Morton, J.W.S. Hearle, *Physical Properties of Textile Fibres*, Woodhead Publishing in Textiles, Cambridge, 2008.
- [28] S. Clifton, B. Thimmappa, R. Selvam, B. Shivamurthy, Polymer nanocomposites for high-velocity impact applications-A review, *Compos. Commun.* 17 (2019) 72–86, <https://doi.org/10.1016/j.coco.2019.11.013>.
- [29] S. Kulkarni, X. Gao, S. Horner, J. Zheng, N. David, Ballistic helmets – their design, materials, and performance against traumatic brain injury, *Compos. Struct.* 101 (2013) 313–331, <https://doi.org/10.1016/j.compstruct.2013.02.014>.
- [30] I.V. Tikhonov, A.V. Tokarev, S.V. Shorin, V.M. Shchetinin, T.E. Chernykh, V. G. Bova, Russian aramid fibres: past – present – future, *Fibre Chem.* 45 (1) (2013) 1–8, <https://doi.org/10.1007/s10692-013-9471-7>.
- [31] A.K. Bandaru, V.V. Chavan, S. Ahmad, R. Alagirusamy, N. Bhatnagar, Ballistic impact response of Kevlar® reinforced thermoplastic composite armors, *Int. J. Impact Eng.* 89 (2015) 1–13, <https://doi.org/10.1016/j.ijimpeng.2015.10.014>.
- [32] A.J. Pennings, A.M. Kiel, Fractionation of polymers by crystallization from solution, III. On the morphology of fibrillar polyethylene crystals grown in solution, *Colloid Polym. Sci.* 205 (2) (1965) 160–162, <https://doi.org/10.1007/bf01507982>.
- [33] A.K. Bandaru, V.V. Chavan, S. Ahmad, R. Alagirusamy, N. Bhatnagar, Ballistic impact response of Kevlar® reinforced thermoplastic composite armors, *Int. J. Impact Eng.* 89 (2015) 1–13, <https://doi.org/10.1016/j.ijimpeng.2015.10.014>.
- [34] A. Zwiijnenburg, *Longitudinal Growth, Morphology and Physical Properties of Fibrillar Polyethylene Crystals*, University of Groningen, 1978.
- [35] B. Kalb, A. Pennings, Spinning of high molecular weight polyethylene solution and subsequent drawing in a temperature gradient, *Polym. Bull.* 1 (12) (1979), <https://doi.org/10.1007/bf00283221>.
- [36] M. Vlasblom, J. Van Dingenen, The manufacture, properties and applications of high strength, high modulus polyethylene fibers, Elsevier eBooks (2009) 437–485, <https://doi.org/10.1533/9781845696801.2.437>.
- [37] A.A. Obaid, S. Yarlagadda, J. Gillespie, Combined effects of kink bands and hygrothermal conditioning on tensile strength of polyarylate liquid crystal co-polymer and aramid fibers, *J. Compos. Mater.* 50 (3) (2015) 339–350, <https://doi.org/10.1177/0021998315574754>.
- [38] J. Holbery, D. Houston, Natural-fiber-reinforced polymer composites in automotive applications, *J. Occup. Med.* 58 (11) (2006) 80–86, <https://doi.org/10.1007/s11837-006-0234-2>.
- [39] R. Malkapuram, V. Kumar, N.Y.S. Negi, Recent development in natural fiber reinforced polypropylene composites, *J. Reinforc. Plast. Compos.* 28 (10) (2008) 1169–1189, <https://doi.org/10.1177/0731684407087759>.
- [40] F. De Oliveira Braga, T.L. Milanezi, S.N. Monteiro, L.H.L. Louro, A.V. Gomes, É. P. Lima, Ballistic comparison between epoxy-ramie and epoxy-aramid composites in Multilayered Armor Systems, *J. Mater. Res. Technol.* 7 (4) (2018) 541–549, <https://doi.org/10.1016/j.jmrt.2018.06.018>.
- [41] M.M. Ahmed, H. Dhakal, Z. Zhang, A. Barouni, R. Zahari, Enhancement of impact toughness and damage behaviour of natural fibre reinforced composites and their hybrids through novel improvement techniques: a critical review, *Compos. Struct.* 259 (2021) 113496, <https://doi.org/10.1016/j.compstruct.2020.113496>.
- [42] D.D. Chung, *Polymer-Matrix Composites: Structure and Processing*, Elsevier eBooks, 2016, pp. 161–217, <https://doi.org/10.1016/b978-0-12-804459-9.00003-8>.
- [43] P. Boisse (Ed.), *Advances in Composites Manufacturing and Process Design*, Woodhead Publishing, Sawston, UK; Cambridge, UK, 2015.
- [44] M. Gascons, N. Blanco, K. Matthys, Evolution of manufacturing processes for fiber-reinforced thermoset tanks, vessels, and silos: a review, *IIE Trans.* 44 (6) (2011) 476–489, <https://doi.org/10.1080/0740817x.2011.590177>.
- [45] K. Balasubramanian, M.T. Sultan, N. Rajeswari, *Manufacturing Techniques of Composites for Aerospace Applications*, Elsevier eBooks, 2018, pp. 55–67, <https://doi.org/10.1016/b978-0-08-102131-6.00004-9>.
- [46] S. Dhanasekar, T.J. Stella, A. Thennozhi, N.D. Bharathi, K. Thiyagarajan, P. Singh, Y.S. Reddy, G. Srinivas, M. Jayakumar, Study of polymer matrix composites for electronics applications, *J. Nanomater.* (2022) 1–7, <https://doi.org/10.1155/2022/8605099>, 2022.
- [47] M. Gascons, N. Blanco, K. Matthys, Evolution of manufacturing processes for fiber-reinforced thermoset tanks, vessels, and silos: a review, *IIE Trans.* 44 (6) (2011) 476–489, <https://doi.org/10.1080/0740817x.2011.590177>.
- [48] M. Holmes, High volume composites for the automotive challenge, *Reinforc. Plast.* 61 (5) (2017) 294–298, <https://doi.org/10.1016/j.repl.2017.03.005>.
- [49] A. Gunge, P.G. Koppad, M. Nagamadh, S. Kivade, K.S. Murthy, Study on mechanical properties of alkali treated plain woven banana fabric reinforced biodegradable composites, *Compos. Commun.* 13 (2019) 47–51, <https://doi.org/10.1016/j.coco.2019.02.006>.
- [50] M. Elkington, D. Bloom, C. Ward, A. Chatzimichail, K. Potter, Hand layup: understanding the manual process, *Adv. Manuf. Polym. Compos. Sci.* 1 (3) (2015) 138–151, <https://doi.org/10.1080/20550340.2015.1114801>.
- [51] M.R. Jamir, M.S. Majid, A. Khasri, *Natural Lightweight Hybrid Composites for Aircraft Structural Applications*, Elsevier eBooks, 2018, pp. 155–170, <https://doi.org/10.1016/b978-0-08-102131-6.00008-6>.
- [52] A.T. Marques, *Fibrous materials reinforced composites production techniques, in: Fibrous and Composite Materials for Civil Engineering Applications*, Woodhead Publishing, Sawston, UK; Cambridge, UK, 2011, pp. 191–215.
- [53] A.S. Perna, A. Viscusi, A. Astarita, L. Boccarusso, L. Carrino, M. Durante, R. Sansone, Manufacturing of a metal matrix composite coating on a polymer matrix composite through cold gas dynamic spray technique, *J. Mater. Eng. Perform.* 28 (6) (2019) 3211–3219, <https://doi.org/10.1007/s11665-019-03914-6>.
- [54] J. Carruthers, *Vacuum bagging process overview*, Coventive Composites (2018). Available online: <https://coventivecomposites.com/explainers/what-is-vacuum-bagging/>. (Accessed 13 July 2019).
- [55] J. Ervina, Z. Ghaleb, S. Hamdan, M. Mariatti, Colloidal stability of water-based carbon nanotube suspensions in electrophoretic deposition process: effect of applied voltage and deposition time, *Composites Part A Applied Science and Manufacturing* 117 (2018) 1–10, <https://doi.org/10.1016/j.compositesa.2018.11.002>.
- [56] M.A. Yalcinkaya, G.E. Guloglu, M. Pishvar, M. Amirhosravi, E.M. Sozer, M. C. Altan, Pressurized infusion: a new and improved liquid composite molding process, *J. Manuf. Sci. Eng.* 141 (1) (2018), <https://doi.org/10.1115/1.4041569>.
- [57] F.S. Awan, M.A. Fakhra, L.A. Khan, U. Zaheer, A.F. Khan, T. Subhani, Interfacial mechanical properties of carbon nanotube-deposited carbon fiber epoxy matrix hierarchical composites, *Compos. Interfaces* 25 (8) (2018) 681–699, <https://doi.org/10.1080/09276440.2018.1439620>.
- [58] H. Ishikawa, H. Takagi, A.N. Nakagaito, M. Yasuzawa, H. Genta, H. Saito, Effect of surface treatments on the mechanical properties of natural fiber textile composites made by VaRTM method, *Compos. Interfaces* 21 (4) (2014) 329–336, <https://doi.org/10.1080/15685543.2013.876322>.
- [59] C. Plummer, P. Bourban, J. Manson, *Polymer Matrix Composites: Matrices and Processing*, Elsevier eBooks, 2016, <https://doi.org/10.1016/b978-0-12-803581-8.02386-9>.
- [60] Y. Leong, S. Thitithanasarn, K. Yamada, H. Hamada, *Compression and Injection Molding Techniques for Natural Fiber Composites*, Elsevier eBooks, 2014, pp. 216–232, <https://doi.org/10.1533/9780857099228.2.216>.
- [61] M. González-López, A. Pérez-Fonseca, R. Manríquez-González, M. Arellano, D. Rodrigue, J. Robledo-Ortiz, Effect of surface treatment on the physical and mechanical properties of injection molded poly(lactic acid)-coir fiber biocomposites, *Polym. Compos.* 40 (6) (2018) 2132–2141, <https://doi.org/10.1002/pc.24997>.
- [62] V.M.K. Werner, R. Krumpholz, C. Rehekampff, T. Scherzer, M. Eblenkamp, Thermoplastic encapsulations of a sensor platform by high-temperature injection

- molding up to 360°C, *Polym. Eng. Sci.* 59 (7) (2019) 1315–1331, <https://doi.org/10.1002/pen.25114>.
- [63] S.C. Joshi, The pultrusion process for polymer matrix composites, in: *Manufacturing Techniques for Polymer Matrix Composites (PMCs)*, Woodhead Publishing, Sawston, UK; Cambridge, UK, 2012, pp. 381–413.
- [64] D. Verma, G. Joshi, R. Dabral, A. Lakhera, Processing and evaluation of mechanical properties of epoxy-filled E-glass fiber-fly ash hybrid composites, Elsevier eBooks (2018) 293–306, <https://doi.org/10.1016/b978-0-08-102292-4.00015-1>.
- [65] J.R. Correia, Pultrusion of Advanced Fibre-Reinforced Polymer (FRP) Composites, Elsevier eBooks, 2013, pp. 207–251, <https://doi.org/10.1533/9780857098641.2.207>.
- [66] Thorsten Mahrholz, Jürgen Mosch, Ulrich Riedel, Dirk Roestermundt, Lars Herbeck, *New High-Performance Fibre Reinforced Materials with Nanocomposites*, 2003, pp. N21–N27.
- [67] K. Pickering, M.A. Efendy, T. Le, A review of recent developments in natural fibre composites and their mechanical performance, *Composites Part A Applied Science and Manufacturing* 83 (2015) 98–112, <https://doi.org/10.1016/j.compositesa.2015.08.038>.
- [68] S. Kumar, R. Prakash, N. Alimuddin, H.K. Choi, B.H. Koo, J.I. Song, H. Chung, H. Jeong, C.G. Lee, Influence of Ti4+ doping on hyperfine field parameters of Mg_{0.95}Mn_{0.05}Fe₂–2x Ti₂O₄ (0 ≤ x ≤ 0.7), *J. Cent. S. Univ. Technol.* 17 (6) (2010) 1139–1143, <https://doi.org/10.1007/s11771-010-0609-y>.
- [69] S. Das, A.K. Singha, A. Chaudhuri, P.K. Ganguly, Lengthwise jute fibre properties variation and its effect on jute–polyester composite, *J. Textil. Inst.* 110 (12) (2019) 1695–1702, <https://doi.org/10.1080/00405000.2019.1613735>.
- [70] V. Mahesh, V. Mahesh, D. Harursamath, Influence of alkali treatment on physio-mechanical properties of jute–epoxy composite, *Advances in Materials and Processing Technologies* 8 (sup2) (2021) 380–391, <https://doi.org/10.1080/2374068x.2021.1934643>.
- [71] J.P. Manaiia, A. Manaiia, Interface modification, water absorption behaviour and mechanical properties of injection moulded short hemp fiber-reinforced thermoplastic composites, *Polymers* 13 (10) (2021) 1638, <https://doi.org/10.3390/polym13101638>.
- [72] A. Vasudevan, S.S. Kumaran, K. Naresh, R. Velmurugan, Experimental and analytical investigation of thermo-mechanical responses of pure epoxy and carbon/Kevlar/S-glass/E-glass/epoxy interply hybrid laminated composites for aerospace applications, *Int. J. Polym. Anal. Char.* 23 (7) (2018) 591–605, <https://doi.org/10.1080/1023666x.2018.1468599>.
- [73] K.C. Shekar, B. Singaravel, S.D. Prasad, N. Venkateshwarlu, B. Srikanth, Mode-I fracture toughness of glass/carbon fiber reinforced epoxy matrix polymer composite, *Mater. Today Proc.* 41 (2020) 833–837, <https://doi.org/10.1016/j.matpr.2020.09.160>.
- [74] M. Ramesh, R. Bhoopathi, C. Deepa, G. Sasikala, Experimental investigation on morphological, physical and shear properties of hybrid composite laminates reinforced with flax and carbon fibers, *Journal of the Chinese Advanced Materials Society* 6 (4) (2018) 640–654, <https://doi.org/10.1080/22243682.2018.1534609>.
- [75] L. Prasad, A. Saini, V. Kumar, Mechanical performance of jute and basalt fiber geo-grid-reinforced epoxy hybrid composite material, *J. Nat. Fibers* 18 (5) (2019) 694–704, <https://doi.org/10.1080/15440478.2019.1645789>.
- [76] J.M. Khare, S. Dahiya, B. Gangil, L. Ranakoti, Influence of different resins on Physico-Mechanical properties of hybrid fiber reinforced polymer composites used in human prosthetics, *Mater. Today Proc.* 38 (2020) 345–349, <https://doi.org/10.1016/j.matpr.2020.07.420>.
- [77] A. Komorek, R. Szczeplaniak, P. Przybyłek, A. Krzyżak, J. Godzimirski, M. Roskowiak, D. Seremak, Properties of multi-layered polymer composites with Vectran fiber reinforcement, *Compos. Struct.* 256 (2020) 113045, <https://doi.org/10.1016/j.compstruct.2020.113045>.
- [78] S. Anidha, S.M. Sekar, E. Natarajan, M. Muthukumar, K. Markandan, C.K. Ang, G. Franz, Preliminary investigations and support for the mechanical and dynamic characteristics of a natural rubber reinforcement in E-glass/CNT/epoxy composite, *Journal of Composites Science* 8 (4) (2024) 140, <https://doi.org/10.3390/jcs8040140>.
- [79] E. Natarajan, T. Sekar, K. Markandan, S. Nesappan, A.D.A. Selvaraj, S.M. Sekar, Structural integrity and mechanical behaviour of magnesium oxide (MgO) as reinforcement in PLA-HDPE composite, *Emergent Materials* 7 (3) (2024) 1283–1294, <https://doi.org/10.1007/s42247-024-00650-z>.
- [80] Santhosh, T. Thangavel, R. Sasikumar, A. Samsudeen, S. Shahzada, V. Sanjay, C. S. Kannan, Mechanical and fire performance of aluminium hydroxide filled E-Glass/phenolic hybrid composites, *Mater. Today Proc.* 37 (2020) 2792–2797, <https://doi.org/10.1016/j.matpr.2020.08.649>.
- [81] N. Maniselvam, Santhosh, R. Sasikumar, P. Murugesan, M. Chandru, Study of corrosion behavior of carbon fiber reinforced plastics (CFRPs), *Mater. Sci. Forum* 969 (2019) 175–180, <https://doi.org/10.4028/www.scientific.net/msf.969.175>.
- [82] National Institute of Justice, *Ballistic Resistance of Body Armor*, vol. 6, NIJ Standard-0101, 2008 223054.
- [83] A.A. Almohandes, M.S. Abdel-Kader, A.M. Eleiche, Experimental investigation of the ballistic resistance of steel-fiberglass reinforced polyester laminated plates, *Composites, Part B* 27 (1996) 447–458.
- [84] P. Zhang, X. Kong, Z. Wang, C. Zheng, H. Liu, G. Shi, J.P. Dear, W. Wu, High velocity projectile impact of a composite rubber/aluminium fluid-filled container, *International Journal of Lightweight Materials and Manufacture* 4 (1) (2020) 1–8, <https://doi.org/10.1016/j.ijlmm.2020.06.007>.
- [85] J.L. Park, Y. Chi, T.J. Kang, Ballistic performance of hybrid panels composed of unidirectional/woven fabrics, *Textil. Res. J.* 83 (5) (2012) 471–486, <https://doi.org/10.1177/0040517512444337>.
- [86] P. Kędzierski, A. Popławski, R. Gieleta, A. Morka, G. Sławiński, Experimental and numerical investigation of fabric impact behavior, *Compos. B Eng.* 69 (2014) 452–459, <https://doi.org/10.1016/j.compositesb.2014.10.028>.
- [87] C.J. Yungwirth, D.D. Radford, M. Aronson, H.N. Wadley, Experiment assessment of the ballistic response of composite pyramidal lattice truss structures, *Compos. B Eng.* 39 (3) (2007) 556–569, <https://doi.org/10.1016/j.compositesb.2007.02.029>.
- [88] F.H. Roubdeneh, G. Liaghat, H. Sabouri, H. Hadavinia, Experimental investigation of impact loading on honeycomb sandwich panels filled with foam, *Int. J. Crashworthiness* 24 (2) (2018) 199–210, <https://doi.org/10.1080/13588265.2018.1426233>.
- [89] P. Xue, X. Peng, J. Cao, A non-orthogonal constitutive model for characterizing woven composites, *Composites Part A Applied Science and Manufacturing* 34 (2) (2003) 183–193, [https://doi.org/10.1016/s1359-835x\(02\)00052-0](https://doi.org/10.1016/s1359-835x(02)00052-0).
- [90] L.S. Paradela, V. Sanchez-Galvez, Analytical simulation of high-speed impact onto composite materials targets, *J. Strain Anal. Eng. Des.* 48 (5) (2013) 282–290, <https://doi.org/10.1177/0309324713488366>.
- [91] M. Pagnoncelli, V. Piroli, D. Romanzini, I.M. Pereira, R.R. Dias, S.C. Amico, A. J. Zattera, Mechanical and ballistic analysis of aramid/vinyl ester composites, *J. Compos. Mater.* 52 (3) (2017) 289–299, <https://doi.org/10.1177/0021998317705976>.
- [92] A. Boroujeni, M. Tehrani, A. Nelson, M. Al-Haik, Hybrid carbon nanotube–carbon fiber composites with improved in-plane mechanical properties, *Compos. B Eng.* 66 (2014) 475–483, <https://doi.org/10.1016/j.compositesb.2014.06.010>.
- [93] A.M. Díez-Pascual, M. Naffakh, C. Marco, M.A. Gómez-Fatou, G.J. Ellis, Multiscale fiber-reinforced thermoplastic composites incorporating carbon nanotubes: a review, *Curr. Opin. Solid State Mater. Sci.* 18 (2) (2013) 62–80, <https://doi.org/10.1016/j.cossms.2013.06.003>.
- [94] F. Inam, D.W.Y. Wong, M. Kuwata, T. Pejjs, Multiscale hybrid micro-nanocomposites based on carbon nanotubes and carbon fibers, *J. Nanomater.* 2010 (1) (2010), <https://doi.org/10.1155/2010/453420>.
- [95] S.C. Joshi, V. Dikshit, Enhancing interlaminar fracture characteristics of woven CFRP prepreg composites through CNT dispersion, *J. Compos. Mater.* 46 (6) (2011) 665–675, <https://doi.org/10.1177/0021998311410472>.
- [96] G.S. Langdon, W.J. Cantwell, Z.W. Guan, G.N. Nurick, The response of polymeric composite structures to air-blast loading: a state-of-the-art, *Int. Mater. Rev.* 59 (3) (2014) 159–177, <https://doi.org/10.1179/1743280413y.0000000028>.
- [97] Y. Liu, S. Kumar, Polymer/carbon nanotube nano composite fibers—A review, *ACS Appl. Mater. Interfaces* 6 (9) (2014) 6069–6087, <https://doi.org/10.1021/am405136s>.
- [98] S. Pichandi, S. Rana, D. Oliveira, R. Fangeiro, Fibrous and composite materials for blast protection of structural elements—a state-of-the-art review, *J. Reinforc. Plast. Compos.* 32 (19) (2013) 1477–1500, <https://doi.org/10.1177/0731684413498297>.
- [99] M. Safdari, M.S. Al-Haik, Optimization of stress wave propagation in a multilayered elastic/viscoelastic hybrid composite based on carbon fibers/carbon nanotubes, *Polym. Compos.* 33 (2) (2011) 196–206, <https://doi.org/10.1002/pc.22137>.
- [100] A. Warrior, A. Godara, O. Rochez, L. Mezzo, F. Luizi, L. Gorbatikh, S.V. Lomov, A. W. VanVuure, I. Verpoest, The effect of adding carbon nanotubes to glass/epoxy composites in the fibre sizing and/or the matrix, *Composites Part A Applied Science and Manufacturing* 41 (4) (2010) 532–538, <https://doi.org/10.1016/j.compositesa.2010.01.001>.
- [101] S. Abrate, *Impact on Composite Structures*, Cambridge Cambridge Univ. Press, 1998.
- [102] W.J. Cantwell, J. Morton, The impact resistance of composite materials d a review, *Composites* 22 (1991) 347–362.
- [103] V. Mahesh, S. Joladarashi, S.M. Kulkarni, An experimental investigation on low-velocity impact response of novel jute/rubber flexible bio-composite, *Compos. Struct.* 225 (2019) 111190, <https://doi.org/10.1016/j.compstruct.2019.111190>.
- [104] T.M. Loganathan, M. Sultan, M.K. Gobalakrishnan, G. Muthaiyah, Ballistic Impact Response of Laminated Hybrid Composite Materials, Elsevier eBooks, 2018, pp. 171–191, <https://doi.org/10.1016/b978-0-08-102292-4.00010-2>.
- [105] S.N. Monteiro, V.S. Candido, F.O. Braga, L.T. Bolzan, R.P. Weber, J.W. Drelich, Sugarcane bagasse waste in composites for multilayered armor, *Eur. Polym. J.* 78 (2016) 173–185, <https://doi.org/10.1016/j.eurpolymj.2016.03.031>.
- [106] N. Naik, P. Shirrao, B. Reddy, Ballistic impact behaviour of woven fabric composites: formulation, *Int. J. Impact Eng.* 32 (9) (2005) 1521–1552, <https://doi.org/10.1016/j.ijimpeng.2005.01.004>.
- [107] M.A. Abtef, F. Boussu, P. Bruniaux, C. Loghin, I. Cristian, Ballistic impact mechanisms – a review on textiles and fibre-reinforced composites impact responses, *Compos. Struct.* 223 (2019) 110966, <https://doi.org/10.1016/j.compstruct.2019.110966>.
- [108] F.S. Da Luz, S.N. Monteiro, E.S. Lima, É.P.L. Júnior, Ballistic application of coir fiber reinforced epoxy composite in multilayered armor, *Mater. Res.* 20 (suppl 2) (2017) 23–28, <https://doi.org/10.1590/1980-5373-mr-2016-0951>.
- [109] F. De Oliveira Braga, L.T. Bolzan, F.J.H.T.V. Ramos, S.N. Monteiro, É.P. Lima Jr., L.C. Da Silva, Ballistic efficiency of multilayered armor systems with sisal fiber polyester composites, *Mater. Res.* 20 (suppl 2) (2018) 767–774, <https://doi.org/10.1590/1980-5373-mr-2017-1002>.
- [110] M.A. Pinheiro, L.G. Gomes, A.C.R. Da Silva, V.S. Candido, R.H.M. Reis, S. N. Monteiro, Guaruman: a natural amazonian fiber with potential for polymer

- composite reinforcement, *Mater. Res.* 22 (suppl 1) (2019), <https://doi.org/10.1590/1980-5373-mr-2019-0092>.
- [111] R. Zah, R. Hischer, A. Leão, I. Braun, Curauá fibers in the automobile industry – a sustainability assessment, *J. Clean. Prod.* 15 (11–12) (2006) 1032–1040, <https://doi.org/10.1016/j.jclepro.2006.05.036>.
- [112] H. Talebi, S. Wong, A. Hamouda, Finite element evaluation of projectile nose angle effects in ballistic perforation of high strength fabric, *Compos. Struct.* 87 (4) (2008) 314–320, <https://doi.org/10.1016/j.compstruct.2008.02.009>.
- [113] Z. Hashin, Failure criteria for unidirectional fiber composites, *J. Appl. Mech.* 47 (1980) 329–334.
- [114] F.K. Chang, L.B. Lessard, Damage tolerance of laminated composites containing an open hole and subjected to compressive loadings: part I-analysis, *J. Compos. Mater.* 25 (1991) 2–43.
- [115] N. Nguyen, A.M. Waas, A novel mixed-mode cohesive formulation for crack growth analysis, *Compos. Struct.* 156 (2015) 253–262, <https://doi.org/10.1016/j.compstruct.2015.11.015>.
- [116] H. Puck, A. Schürmann, Failure analysis of FRP laminates by means of physically based phenomenological models, *Compos. Sci. Technol.* 62 (2002) 1633–1662.
- [117] C.R. Schultheisz, A.M. Waas, Compressive failure of composites, part I: testing and micromechanical theories, *Prog. Aero. Sci.* 32 (1996) 1–42.
- [118] S. Basu, A.M. Waas, D.R. Ambur, Compressive failure of fiber composites under multi-axial loading, *J. Mech. Phys. Solid.* 54 (3) (2005) 611–634, <https://doi.org/10.1016/j.jmps.2005.09.004>.
- [119] C.H. Wang, C.N. Duong, Failure criteria. Bonded Joints and Repairs to Composite Airframe Structures, Academic Press, 2016, pp. 21–45.
- [120] B. Zhang, X. Guo, Y. Liu, L. Lang, S. Tan, Study of glass laminate configurations on ballistic resistance of novel lightweight sapphire transparent laminated structures, *International Journal of Lightweight Materials and Manufacture* 4 (4) (2021) 397–404, <https://doi.org/10.1016/j.ijlmm.2021.05.002>.
- [121] R. Jones, *Mechanics of Composite Materials*, McGraw-Hill, Washington, DC, 1975.
- [122] S. Tsai, Strength characteristics of composite materials, Report, NASA CR-224 (1965) 1–58.
- [123] S.W. Tsai, E.M. Wu, A general theory of strength for anisotropic materials, *J. Compos. Mater.* 5 (1971) 58–80.
- [124] Z. Hashin, Failure criteria for unidirectional fiber composites, *J. Appl. Mech.* 47 (1980) 329–334.
- [125] C.G. Davila, P.P. Camanho, C.A. Rose, Failure criteria for FRP laminates, *J. Compos. Mater.* 39 (2005) 323–345.
- [126] S.T. Pinho, C.G. Davila, P.P. Camanho, L. Lannucci, P. Robinson, Failure models and criteria for FRP under in-plane or three-dimensional stress states including shear non-linearity, NASA Langley Res. Center, Hampton, VA. NASA/TM-2005-213530 (2005).
- [127] S.I. Thorsson, A.M. Waas, M. Rassaian, Low-velocity impact predictions of composite laminates using a continuum shell based modeling approach part A: impact study, *Int. J. Solid Struct.* 155 (2018) 185–200, <https://doi.org/10.1016/j.ijsolstr.2018.07.020>.
- [128] K. Czech, R. Oliwa, D. Krajewski, K. Bulanda, M. Oleksy, G. Budzik, A. Mazurkow, Hybrid polymer composites used in the arms industry: a review, *Materials* 14 (11) (2021) 3047, <https://doi.org/10.3390/ma14113047>.
- [129] Company, T. B. R. (n.d.). Armor materials market report 2024 - armor materials market outlook and scope by 2033. The Business Research Company. <https://www.thebusinessresearchcompany.com/report/armor-materials-global-market-report>.
- [130] E. Natarajan, M. Ramasamy, G. Anbuhezhiyan, S.M. Sekar, M. Vignesh, Enriching grain refinement on improving mechanical and corrosion properties of graphene reinforced magnesium composites, *Results in Materials* (2025) 100689, <https://doi.org/10.1016/j.rinma.2025.100689>.
- [131] K.P.S. Perumal, L. Selvarajan, S.M. Sekar, E. Natarajan, Examining thermogravimetric response and morphological alterations in epoxy composites with hybrid ceramic fillers integration, *Mater. Chem. Phys.* 325 (Jul. 2024) 129755, <https://doi.org/10.1016/j.matchemphys.2024.129755>.